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Numerical simulation of fatigue crack propagation under biaxial tensile loadings with phase differences

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ABSTRACT

Fatigue crack propagation under the biaxial tensile loading, which loading directions are normal and parallel to the initial crack position, is highlighted in this study. Most of in-service structures and vessels are subjected to many types of loading. Generally, these loadings have different axial components with different phases. However, the structural integrities of structures and vessels are evaluated according to design codes based on theoretical and experimental investigations under a uniaxial loading condition. Most of these codes are based on the S–N curves approach. An approach that does not use S–N curves has been favored by researchers, with the fracture mechanics approach preferred for evaluating the fatigue life of structures. An advanced fracture mechanics approach was developed based on the Re-tensile Plastic zone Generating (RPG) stress criterion for fatigue crack propagation. In this study, fatigue crack propagation tests under biaxial loading with six different phase and loading conditions are performed and the effect of the phase difference under biaxial loading is evaluated. A numerical simulation method of fatigue crack propagation based on the RPG stress criterion under different biaxial loading phase conditions is presented and compared to measured data.

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1. Introduction

Most of in-service structures and vessels are subjected to many types of loading. Generally, these loadings have different axial components and different phases. In practice, however, the structural integrity of most working structures are assessed by following the design codes of each structure, which are based on theoretical and experimental investigations under uniaxial loading conditions.

Fatigue strength under biaxial loading has been investigated via S–N curve and fracture mechanics approaches. The researches based on the fracture mechanics approach [1–4] could not reach a definite conclusion regarding the effect of biaxial loading on fatigue crack growth behavior because of conflicting results. However, the research based on the S–N curves [5,6] gave only measured S–N curves for individual loading conditions. Hence, it is very important to establish a quantitative evaluation procedure for fatigue crack growth under biaxial loading conditions.

Authors have been favoring the advantage of the fracture mechanics approach for evaluating the fatigue life of structures, using an advanced fracture mechanics approach based on the Re-tensile Plastic zone Generating (RPG) stress criterion for fatigue crack propagation was developed by Toyosada et al. [7]. Moreover, they developed a numerical simulation code of fatigue crack propagation, which considered the fatigue crack opening/closing phenomena caused by crack wake over crack surfaces and implemented the RPG stress criterion as the fatigue crack propagation law. The validity of the estimated fatigue crack propagation histories under stress conditions of variable amplitude was confirmed by measured fatigue crack growth curves [7]. These comparisons, however, were performed under uniaxial loading conditions. The aim in this study was to extend this approach to biaxial loading problems, which loading directions are normal and parallel to the initial crack position, by evaluating the structural integrity related to the fatigue strength from a practical point of view.

Fatigue crack propagation tests under biaxial loading with six different phase conditions were performed in order to highlight the effect of the phase difference under biaxial loading on the fatigue crack growth behavior. A numerical simulation method of fatigue crack propagation based on the RPG criterion under biaxial loading with different loading phases is proposed.

2. Fatigue crack propagation test under biaxial loading

2.1. Overview of the experiment

Cruciform-shaped cracked specimens shown in Fig. 1 were prepared for fatigue crack propagation tests under biaxial loading conditions. In addition, a center-cracked tensile (CCT) specimen shown in Fig. 2 was prepared for the test under uniaxial loading conditions. All the specimens were formed from the same mild steel plate (grade KA standardized by classification society ClassNK). The chemical composition and mechanical properties of the tested steel are listed in Table 1. Fatigue crack propagation tests under biaxial loading conditions were performed by using a testing system that consisted of four independent servo loading actuators that enabled controlled variable loading under different phases, see Fig. 3. The applied loading conditions for each specimen are listed in Table 2 and the schematic illustration of load waveforms are shown in Fig. 4.

2.2. Fractured surface observations

It is generally accepted that fatigue crack opening/closing behavior is induced by the plastic deformed layer (crack wake) over the fatigued crack surfaces. However, the roughness of the crack surface also plays a role in inducing the crack closure.

The fractured crack surfaces were observed by low-voltage scanning electron microscopy (LV-SEM) to investigate the degree of contribution of such crack closure induced mechanisms under biaxial loading with different loading phases. The observed crack surfaces are shown in Fig. 5. The surfaces observed were about 20 mm from the tip of the initial notch. Little difference of each biaxial specimen